Enhanced Reflectivity and Stability of High-Temperature LPP Collector Mirrors

Torsten Feigl[*a], Sergiy Yulin[a], Nicloas Benoit[a], Marco Perske[a], Mark Schürmann[a], Norbert Kaiser[a], Norbert R. Böwering[b], Oleh V. Khodykin[b], Igor V. Fomenkov[b], David C. Brandt[b]
[a]Fraunhofer IOF, Albert-Einstein-Str. 7, 07745 Jena, Germany
[b]Cymer Inc., 17075 Thornmint Court, San Diego, CA USA 92127-1712

ABSTRACT

The source output power and lifetime, including the collector optics lifetime, are among the key issues for EUV lithography systems. In order to meet the requirements for the EUV collector mirror, both the reflectivity and the long-term thermal stability of its multilayer coating have been enhanced considerably during recent development efforts. Sub-aperture ellipsoidal mirrors of different substrate materials with outer diameters of about 320 mm were coated with laterally graded high-temperature multilayers. The interface-engineered Mo/Si multilayer mirror (MLM) coatings were optimized in terms of high peak reflectivity at 13.5 nm and working temperatures above 400°C. Thin barrier layers were introduced on both interfaces to block thermally induced interdiffusion processes of molybdenum and silicon and to provide long-term optical stability of the coating at elevated temperatures. A normal-incidence reflectance of R ~ 60 % at 13.5 nm was measured on Si wafer samples after heating up to 600°C. No degradation of the optical properties of these multilayer coatings occurred during both long-term heating tests and multiple annealing cycles. On highly polished collector substrates with improved surface roughness a reflectance for s-polarized light exceeding peak values of R = 57 % was obtained. With optimized layer gradient the degree of wavelength matching was improved, as well, resulting in peak reflectivity values above 56 % throughout the clear aperture for a series of measurement points across the mirror. The corresponding area-weighted 2% in-band average reflectance for this collector mirror coating exceeds 52 % for unpolarized light.

Keywords: EUV collector mirror, multilayer mirror coatings, thermal stability, collector lifetime, optics lifetime

1. INTRODUCTION

For laser-produced plasma (LPP) extreme ultraviolet (EUV) light sources the most efficient scheme for the collection of the generated radiation is based on the use of large ellipsoidal collector mirrors. Such condenser mirrors are located fairly close to the plasma to capture a large fraction of the emitted usable radiation. They have to reflect the EUV light at angles close to normal incidence due to this geometry. Thus, a mirror coating is required that employs multi-layers producing sufficiently high average reflectance and maintaining their reflective properties at elevated temperatures in the given environment near the plasma. Cymer's EUV source concept for high-volume production tools is based on a high-repetition rate CO_2 - laser generated tin droplet plasma with at least 5 sr light collection angle. The operation of a corresponding prototype system at 13.5 nm wavelength with a heated collector (C1) mirror was reported previously [1]. We have also given detailed descriptions of the EUV source collector concept and early test results as well as developments of high-temperature stable multilayer coatings [2, 3]. In this report we give an update on recent advancements in the development of coatings with higher reflectance and enhanced thermal stability during long-term testing. We describe the improved coating results for ellipsoidal collectors of sub-aperture size with diameters up to 320 mm that were manufactured to serve as proof-of-concept for the EUV light collection from LPP sources.

In the favored configuration for light collection the laser is focused onto the droplet target through a central opening in the mirror. The collector surface has the shape of a section of a prolate spheroid in order to image the EUV emitting plasma region to the intermediate focus (IF) position which constitutes the interface to the illuminator section of the scanner module. This scheme is illustrated in figure 1.

* Torsten.Feigl@iof.fraunhofer.de; phone: +41 (0)3641 807240; fax: +41 (0)3641 8072601

Advances in X-Ray/euv Optics and Components III, edited by Ali M. Khounsary, Christian Morawe, Shunji Goto
Proc. of SPIE Vol. 7077, 70771W, (2008) · 0277-786X/08/$18 · doi: 10.1117/12.802322

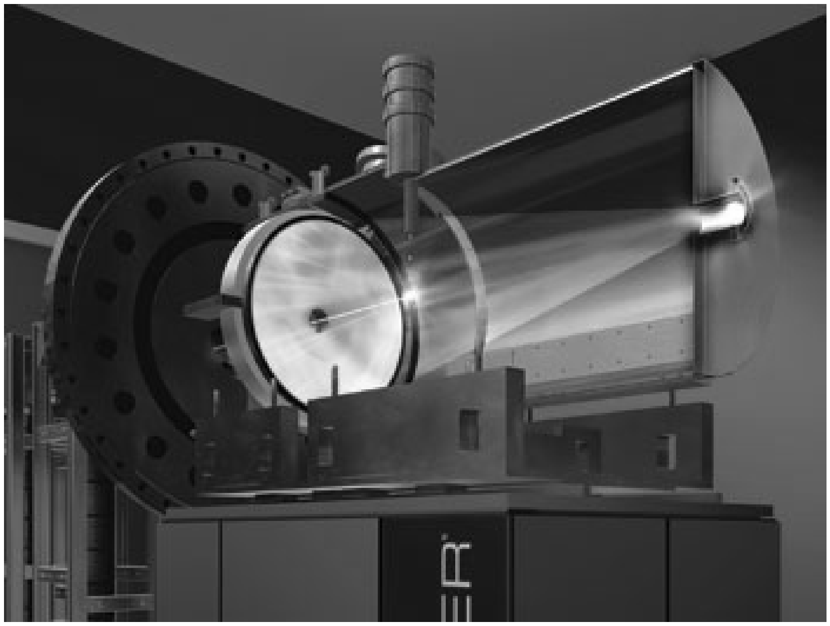

Figure 1: View of source chamber with LPP – droplet target source and light collection configuration with large collector mirror for refocusing the EUV radiation from the LPP to the IF.

2. OPTICAL DESIGN CONCEPT AND COLLECTOR LIFETIME

As described in the introduction a single-shell ellipsoidal collector having a collection solid angle of at least 5 sr is chosen as the preferred geometric configuration. Matching of the acceptance cone of the illuminator at the IF position for a given collector diameter (D) and focal distance (f) results in a configuration as illustrated schematically in figure 2. For proof-of-concept we have opted to first build a sub-aperture mirror with half the diameter but the same elliptical cross section for initial testing and system integration (corresponding to 1.6 sr collection solid angle, see figure 2).

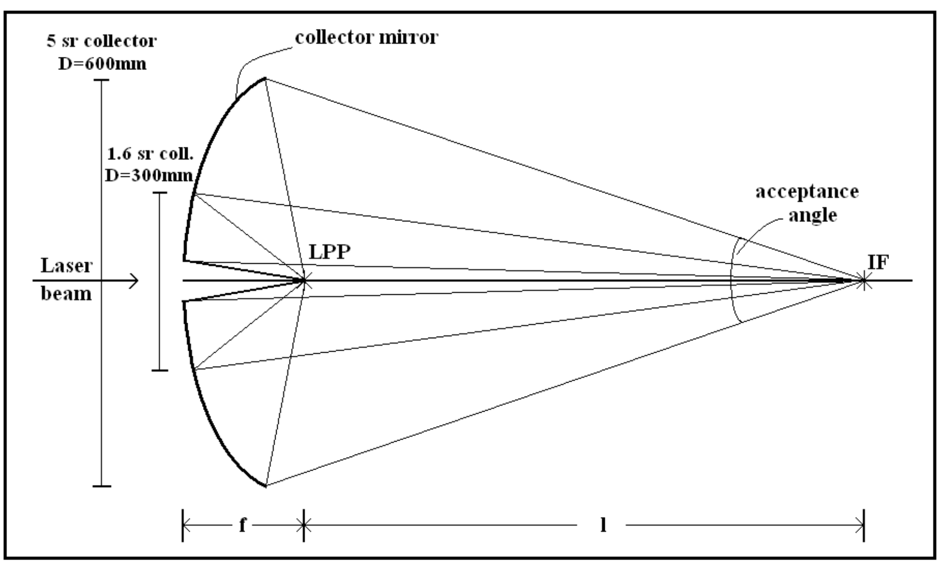

Figure 2: Schematics of light collection geometry with ellipsoidal collector and refocused image at IF. Examples of a 5 sr collector (600 mm diameter) and a 1.6 sr sub-aperture (half-size) configuration are shown in comparison.

There are two important technical aspects that greatly influence the development of normal-incidence EUV collectors: the optical performance and the coating lifetime. The optical configuration shown in Figs. 1, 2 offers several performance advantages. Normal-incidence mirrors can be designed with high light collection efficiency since the small etendue of the LPP source supports large collection angles. In this way a large fraction of the generated EUV radiation can be transferred to the illuminator module. The reflectance of Mo/Si-based multilayer coatings near 13.5 nm is high and average reflectivities of around $\langle R_{av} \rangle = 50$ % are within reach even for specialized coatings and for incidence angles ranging from 5° to 35° for such mirrors. The wavelength dependence of the reflectance of the multilayer coating induces a pre-filtering of the spectrum emitted from the source and provides a higher degree of spectral purity as compared to coatings for grazing-incidence collectors. At comparable EUV power levels at IF this leads to a significantly lower out-of-band radiation dose for the sensitive scanner optics. Furthermore, a mechanically robust thick shell can be used as mirror substrate having a high thermal load capacity and thus allowing for effective thermal management at the backside with minimal mirror deformation.

The lifetime of the collector mirror also plays a major role. It is directly connected with the reflectance stability and coating lifetime. For high collection efficiency the mirror has to be located in close proximity to the plasma. During source operation substantial plasma heating of the mirror surface occurs and the MLM employed for C1 has to exhibit enhanced thermal stability compared to binary layer Mo/Si coatings that degrade by layer inter-diffusion at temperatures above 150°C - 200°C [4, 5]. Due to the significant absorption in the multilayer stack the radiation dose will also lead to thermal energy transfer to the coating via generated secondary electrons. There are also energetic particles emitted from the plasma that will impact the mirror surface and can potentially cause coating erosion if they are not completely eliminated before reaching the mirror. Consequently, sufficient space has to be available for debris mitigation between the plasma and the collector mirror. In addition, source material may diffuse into the multilayer and reduce the layer contrast. Furthermore, target material (Sn) may accumulate on top of the coating leading to absorption of EUV radiation and reduction of mirror reflectivity. A similar effect may arise from contaminants present in the source chamber during operation. A C1 operational lifetime of one year is proposed as a reasonable lifetime target value. Cymer's collector mirror concept and IOF's coating approach is geared towards the optimization of the collector performance in view of these critical optical and lifetime aspects. In this paper we would like to focus on our recent improvements with respect to EUV reflectivity and thermal stability.

3. HIGH-TEMPERATURE MULTILAYER DEVELOPMENT

In order to achieve a multilayer coating with good optical properties a high contrast between the Mo absorber layer and the Si spacer layer of the coating has to be achieved. However, this ideal situation is not met in practice since silicide formation occurs at each interface between Mo and Si, and h-$MoSi_2$ layers are created by intermixing (see Fig. 3). Moreover, it is known that annealing at elevated temperatures accelerates the growth of such inter-diffusion layers further [4, 5]. Consequently, interface stabilization for Mo/Si coatings has been addressed by a number of research groups in the past [6-10]. A promising concept is the introduction of ultra-thin diffusion barrier layers at the interfaces to inhibit layer intermixing. This is also illustrated schematically in figure 3. Inert layers with good thermal, optical and structural properties provide a solution that effectively excludes contrast reduction by silicide formation, gives interface stability at elevated temperatures, and leads to only a small reduction of EUV reflectance due to increased absorption.

Interface-engineered multilayer systems with several types of barrier layers were studied in detail previously [8, 11]. For the ML coating of test samples we used an industrial magnetron sputtering system (MRC 903 M) that was described earlier [8, 12]. Long-term temperature MLM stability up to T = 500 °C could be achieved in these tests [11]. A number of such layer systems exhibited also very high EUV reflectances. These promising results with respect to thermal stability and optical performance encouraged us to continue the development with interface-engineered MLMs in order to explore their full potential for use with the coating of the EUV source collector mirror.

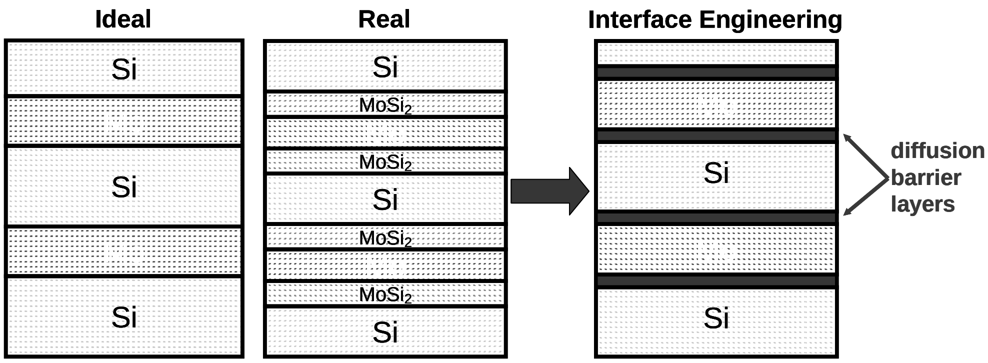

Figure 3: Schematics of interface engineered multilayers. Thin diffusion barrier layers are introduced at the interfaces between Mo and Si layers.

Deposition process optimization for a candidate Mo/Si-based multilayer design with highly inert barrier layers has now lead to the development of coatings with stable EUV reflectance properties during long-term heating tests at temperatures up to T = 600 °C. Results for EUV reflectivity curves for silicon wafer samples coated with the interface-engineered ML are given in figure 4. The as-deposited case is shown in direct comparison with results obtained after prolonged heating for 100 hours at temperatures of 400 °C, 500 °C, and 600 °C. A wavelength shift of + 0.5 % occurs after initial annealing at T = 400 °C. However, the internal structure is stabilized for this type of coating design and the optical properties of the mirrors stay constant even when annealed at T = 600 °C. Peak EUV reflectivities near R = 60 % were routinely obtained for these coatings. Structural investigations of the multilayer stack were also carried out using transmission electron microscopy (TEM). A high layer contrast without any signs of inter-diffusion could be confirmed. Images obtained by TEM before and after annealing at T = 500 °C are also presented in figure 4. In addition, the surfaces were studied by atomic force microscopy (AFM) after deposition and after annealing. Only a small increase of the high spatial frequency roughness (HSFR) was observed (< 20 % increase).

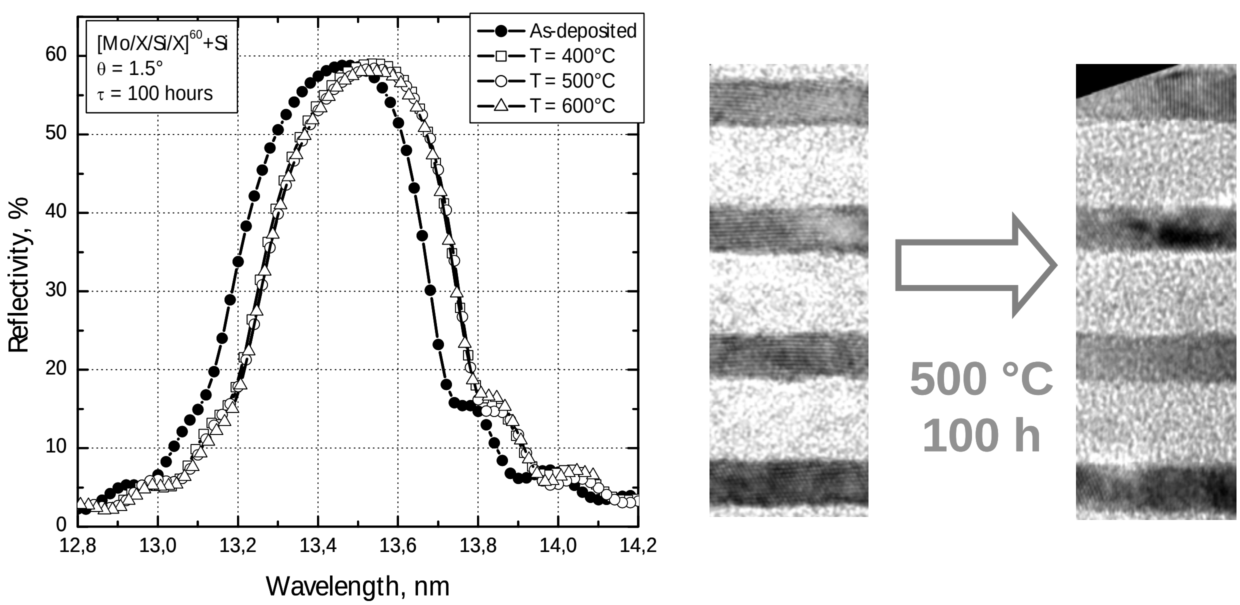

Figure 4: Reflectivity curves of interface-engineered multilayer coatings on Si wafer test samples after deposition and after annealing at T = 400, 500, and 600 °C. (left). Also shown are high-resolution cross-sectional TEM images of the coatings after deposition and after annealing to 500 °C (right).

4. COLLECTOR MIRROR COATING AND RELATED TECHNOLOGY

For the coating of large mirror substrates, the DC magnetron new EUV sputtering system NESSY was used (see Fig. 5) [13]. It has a cryo-pumped ultra-high vacuum chamber that is equipped with four rectangular magnetrons in sputter-down configuration with variable target-substrate distance. Rotating and fast-spinning substrates with diameters up to D = 665 mm can be coated. The deposition of layers with laterally graded thickness on curved substrates can be accomplished by the use of moving shutters. The chamber has a load-lock system located inside of the clean room for substrate insertion. Typically, a base pressure of < 8 $x10^{-9}$ mbar is achieved. Coatings on both flat and curved substrates can be produced with pre-determined deposition recipes. In order to provide highly accurate and reproducible layer deposition procedures for graded MLM coatings the system is equipped with fully programmable process controls.

Figure 5: Photograph of the magnetron sputtering system NESSY.

5. EUV REFLECTIVITY MEASUREMENT RESULTS

Several ellipsoidal sub-aperture collectors with outer diameters up to D = 320 mm were coated with high-temperature multilayers with the NESSY machine. Previously, we have reported EUV reflectivity results obtained for a first mirror substrate of this size [2, 3]. It had a surface HSFR in the range of ~ 0.6 nm, as measured by AFM. After annealing to a temperature of T = 400 °C, peak EUV reflectances of around R_p^s = 40 % were measured for this collector for a series of equidistant measurement points across the surface using s-polarized synchrotron radiation. The EUV reflectivity data were obtained with the EUV reflectometer of the Physikalisch-Technische Bundesanstalt (PTB) at the Berlin electron storage ring using s-polarized light [14].

After further optimization of the high-temperature MLM deposition processes and for a collector substrate with improved surface quality (AFM HSFR near 0.3 nm) a significant enhancement of the peak reflectance could be achieved. After multilayer deposition (number of periods: N = 60) and annealing at T = 400 °C for 1 hour, the collector was sent to PTB and its EUV reflectivity was measured with synchrotron radiation (spot size on surface < 1.5 mm diameter). Figures 6 - 8 show the corresponding reflectance results obtained with s-polarized light for two series of measurement points across the mirror. The peak reflectance values of the reflectivity curves are displayed in figure 6 as a function of mirror radius. These peak reflectances were found to be 56 % or larger at all measured positions within the clear aperture of the collector and are also nearly constant as a function of radius. The maximum reflectance measured

was R_m^s = 57.7 %. For a Si wafer witness plate positioned at the center of the collector during the deposition process which was also annealed at 400°C a peak reflectance of R_p^s = 58.2 % was measured at near-normal incidence.

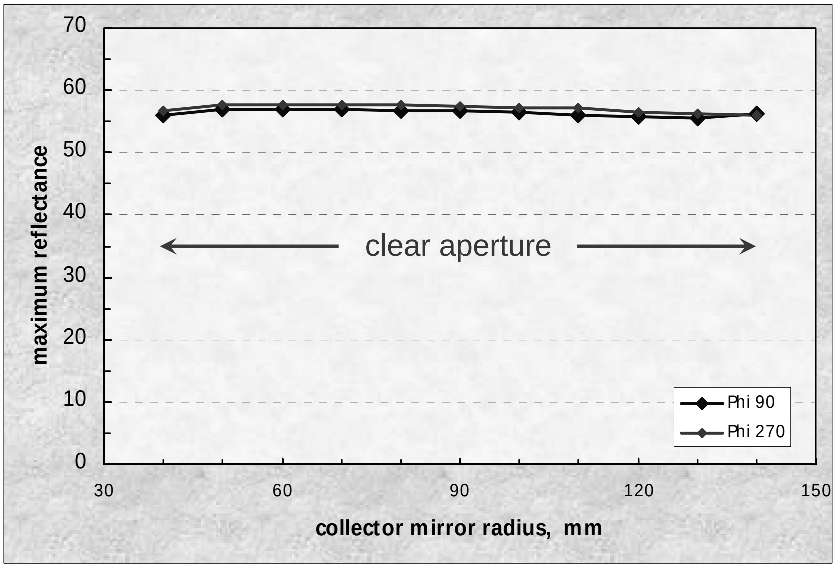

Figure 6: Peak reflectance values as a function of mirror radius obtained for s-polarized light.

Figure 7 shows one series of corresponding reflectivity curves as a function of wavelength. The lateral multilayer thickness gradient was optimized using test samples prior to collector coating in order to meet the specified center wavelength of 13.50 nm. A central wavelength of λ_c = 13.47 nm was achieved on the collector with substantially improved wavelength matching of the reflectivity curves compared to the earlier coating results [3]. The full-width at half-maximum of the reflectivity curves is typically > 0.48 nm.

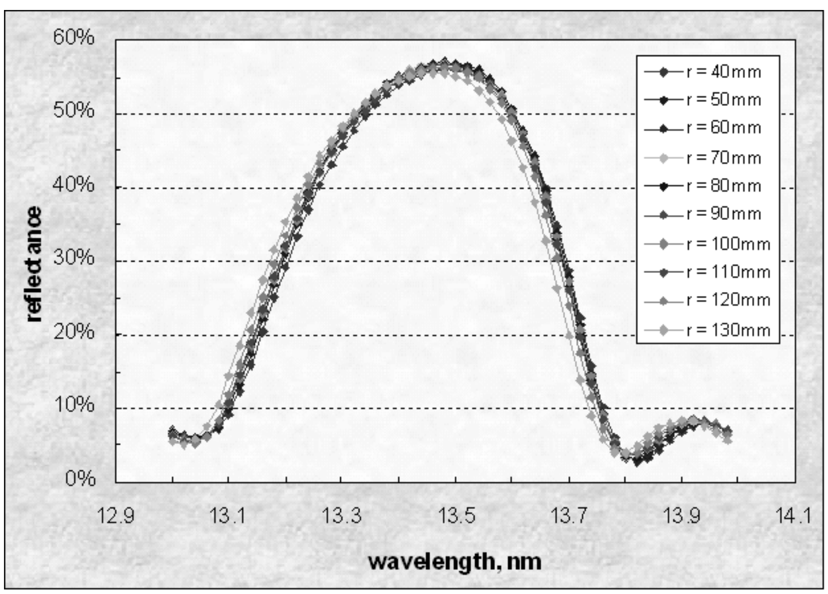

Figure 7: Reflectivity curves at different mirror radii as a function of wavelength.

The reflectance measurements are illustrated in some more detail in figure 8. The behavior of the reflectivity curves for the two series of measurement points is very similar. For the range of radii from 40 mm to 130 mm the corresponding angles of incidence vary from 4.8° to 15.3°. The 2 % bandwidth region that characterizes the radiation that is used for exposing the wafer is also indicated in the figure. Most of the measured reflectance values were found to be above the 50 % level for the wavelength range of (13.47 ± 0.13) nm.

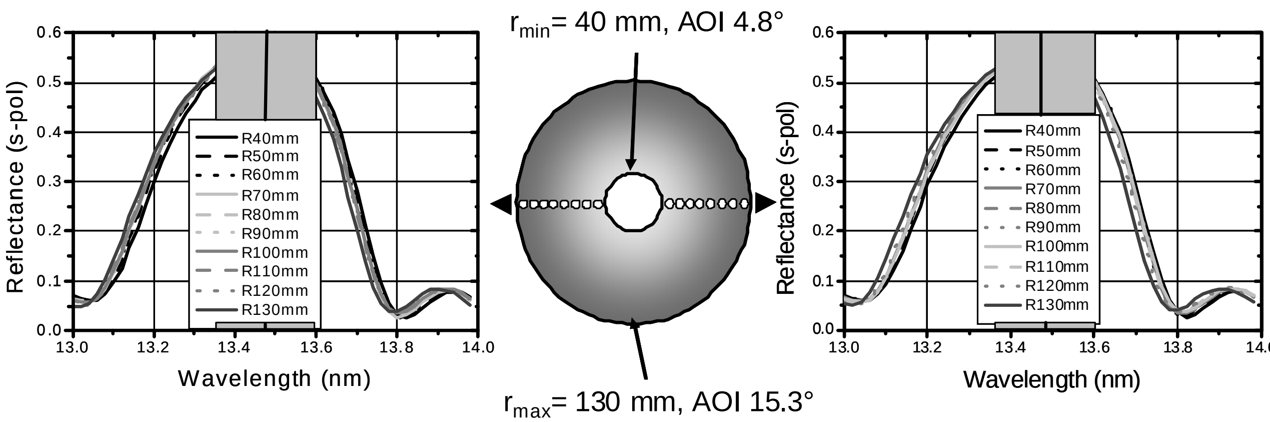

Figure 8: Measured mirror reflectivity curves for two series of points across the mirror ranging from radii of 40 mm to 130 mm. Also indicated in the figures is the region of 2 % bandwidth (shaded).

6. COLLECTOR MIRROR AVERAGE REFLECTANCE

An important value characterizing the quality of a collector mirror of given shape for its use in an EUV source is its average reflectance. In this case it is not the peak reflectance, but rather the in-band EUV reflectance that is of key interest, because predominantly radiation within a 2 % bandwidth around 13.5 nm is used for exposure at the wafer level. Furthermore, since the laser-produced plasma emits unpolarized radiation, the contributions from both s- and p-polarized light should be taken into account. For p-polarized light the peak reflectance decreases as the incidence angle is increased, corresponding to larger radial positions on the mirror. On the other hand, the contributing area of the reflecting surface on the ellipsoidal mirror increases with mirror radius and partially compensates this decrease in reflectivity.

By weighing the contributing surface area of the mirror and taking into account the corresponding measured reflectance, the area-weighted average in-band reflectance (2 % bandwidth) for s-polarized light was determined to be $\langle R_{2\%}^{s} \rangle$ = 54.8 %; the corresponding area-weighted peak reflectance was $\langle R_{p}^{s} \rangle$ = 56.8 %. The analogous values for the case of unpolarized incident light were calculated by modeling of the EUV reflectivity of the multilayer stack. Excellent agreement between modeled and measured curves was achieved at near-normal incidence angles. With the help of the model, the corresponding average of the reflectances for s- and p- polarized light could be determined. Based on the modeling, the area-weighted average peak reflectance for the case of unpolarized incident light was found to be $\langle R_{p}^{u} \rangle$ = 54.0 % at λ_c = 13.47 nm, while the area-weighted average in-band reflectance (2 % bandwidth) was determined to be $\langle R_{2\%}^{u} \rangle$ = 52.6 %. The average in-band reflectance attained for this sub-aperture collector thus exceeds the target value of $\langle R_{2\%}^{u} \rangle$ = 50 % that is commonly used in the road maps for production tools. For a full-size collector with ~5 sr light collection, however, the incidence angles will increase to values of about 35° near the outer edge of the mirror. This can lead to a reduction of the average reflection by a several percent compared to a 1.6 sr collector, with the actual value depending on the specific optical geometry and size of the mirror. Nevertheless, the data obtained so far are very encouraging for our MLM coating development towards the goal of achieving an average in-band reflectance of 50 % for the collector mirror.

7. SUMMARY AND CONCLUSIONS

Significant improvements in the development of high-temperature stable multilayer coatings and in the deposition of such coatings on sub-aperture collector mirrors of close to 300 mm optical diameter have been realized. Superior temperature stability up to T = 600 °C with EUV reflectance near 60 % was achieved for interface-engineered ML coatings on test samples. With an optimized deposition process a ML coating with a measured maximum reflectance of 57.7 % after annealing was deposited on a collector mirror substrate with improved roughness leading to an average area-weighted in-band reflectance of 52.6 % for unpolarized light. Compared to earlier results this is a substantial enhancement of EUV collector reflectance. The successful realization of the high-temperature sub-aperture mirrors represents a major step towards the implementation of elevated-temperature collector concepts and underlines the great potential of temperature-stable interface-engineered EUV multilayer coatings for future high-volume production.

ACKNOWLEDGEMENTS

The authors would like to thank all members of the IOF coating project team and of the Cymer EUV development group for their continued support. In particular, we would like to thank Wieland Stöckl, Michael Scheler, Thomas Müller, Hagen Pauer, Tino Benkenstein, Sophie Schröder, Slava Nesterenko, Wilko Fuhlrott and Ronald Schmidt from IOF as well as Alex I. Ershov, A. N. Bykanov, David W. Myers, Juan A. Chavez, Rodney D. Simmons from Cymer. We are very grateful to Christian Laubis, Frank Scholze, Christian Buchholz, Heike Wagner and Sven Plöger for reflectivity measurements at Physikalisch-Technische Bundesanstalt, Berlin, and also thank Ute Kaiser, University of Ulm, for providing us with TEM data of MLM coatings.

REFERENCES

1. D. C. Brandt, I. V. Fomenkov, A. I. Ershov, W. N. Partlo, D. W. Myers, N. R. Böwering, A. N. Bykanov, G. O. Vaschenko, O. V. Khodykin, J. R. Hoffman, E. Vargas L., R. D. Simmons, J. A. Chavez, C. P. Chrobak, in: *Emerging Lithographic Technologies XI*, edited by Michael J. Lercel, Proc. of SPIE Vol. **6517**, 65170Q (2007).
2. N. R. Böwering, A. I. Ershov, W. F. Marx, O. V. Khodykin, B. A. M. Hansson, E. Vargas L., Juan A. Chavez, I. V. Fomenkov, D. W. Myers, D. C. Brandt, in: *Emerging Lithographic Technologies X*, edited by Michael J. Lercel, Proc. of SPIE Vol. **6151**, 61513R (2006).
3. T. Feigl, S. Yulin, N. Benoit, N. Kaiser, N. R. Böwering, A. I. Ershov, O. V. Khodykin, J. W. Viatella, K. A. Bruzzone, I. V. Fomenkov, D. W. Myers, in: *Emerging Lithographic Technologies X*, edited by Michael J. Lercel, Proc. of SPIE Vol. **6151**, 61514A (2006).
4. D. G. Stearns, M. B. Stearns, Y. Cheng, J. H. Stith, N. M. Ceglio, J. Appl. Phys. **67**, 2415-2427 (1990).
5. T. Feigl, H. Lauth, S. Yulin, N. Kaiser, Microelectronic Engineering **57-58**, 3-8 (2001).
6. V. V. Kondratenko, Yu. P. Pershin, O. V. Poltseva, A. I. Fedorenko, E. N. Zubarev, S. A. Yulin, I. V. Kozevnikov, S. I. Sagitov, V. A. Chirkov, V. E. Levashov, A. V. Vinogradov, Appl. Opt. **32**, 1811-1816 (1993).
7. H. Takenaka and T. Kawamura, J. Electron. Spec. Rel. Phenom. **80**, 381-384 (1996).
8. T. Feigl, S. Yulin, N. Kaiser, R. Thielsch, in: *Emerging Lithographic Technologies IV*, edited by Elizabeth A. Dobisz, Proc. SPIE Vol. **3997**, 420-430 (2000).
9. S. Braun, H. Mai, M. Moss, R. Scholz, A. Leson, Jpn. J. Appl. Phys. **41**, 4074-4081 (2002).
10. S. Bajt and D. G. Stearns, Appl. Opt. **44**, 7735-7743 (2005).
11. S. Yulin, N. Benoit, T. Feigl, N. Kaiser, in: *Emerging Lithographic Technologies IX*, edited by R. S. Mackay, Proc. of SPIE Vol. **5751**, 1155-1161 (2005).
12. T. Feigl, S. Yulin, T. Kuhlmann, N. Kaiser, Jpn. J. Appl. Phys. **41**, 4082-4085 (2002).
13. T. Feigl, S. Yulin, N. Benoit, N. Kaiser, Microelectronic Engineering **83**, 703-706 (2006).
14. J. Tümmler, H. Blume, G. Brandt, J. Eden, B. Meyer, H. Scherr, F. Scholz, F. Scholze, G.Ulm, in: *Emerging Lithographic Technologies VII*, edited by R. L. Engelstad, Proc. SPIE Vol. **5037**, 265-273 (2003).